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ABSTRACT

Demonstrations in astronomy classes seem to be more necessary than in physics classes for three reasons. First, many of the events are very large scale and impossibly remote from human senses. Secondly, while physics courses use discussions of one- and two-dimensional motion, three-dimensional motion is the normal situation in astronomy; thus, there is greater complexity. Thirdly, students attracted to popular astronomy courses seem less equipped to follow mathematical concepts. For these and other reasons, good astronomy demonstrations must be developed. Four such demonstrations are described: (1) lunar diurnal tides; (2) elliptical orbits of binary stars (in which a set of two or more charts is used to explain details of the motion of binary stars, especially the relationship between theoretical motion and actual appearance from the viewer's vantage point on earth); (3) eclipse motion; and (4) absorption spectra, noting that absorption cells containing solutions of rare earth compounds are better for use with large classes than sodium flames. (JN)

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ASTRONOMY DEMONSTRATIONS AND MODELS

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Invited paper given to the American Association of Physics Teachers meeting on January 28, 1986 at Atlanta, GA.

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An invited paper given to the American Association of Physics Teachers Meeting January 28, 1986 at Atlanta, GA by Dr. Charles A. Eckroth, St. Cloud State U, St. Cloud, MN 56301

Almost every physics teacher understands the value of good classroom demonstrations. At AAPT meetings like this one there are always several new and improved demonstrations shown.

Before beginning to teach astronomy, I taught physics courses and so it was natural to continue the habit of using demonstrations. Sometimes I found it possible to use the same ones I had used in physics classes. But, I found that in Astronomy classes demonstrations seemed to be more necessary for three reasons.

First, many of the events are very large scale and impossibly remote from us. Secondly, while physics courses an go a long with discussions of one and two dimensional motion, three-dimensional motion is the normal situation in astronomy. Thus there is greater complexity. Thirdly, and I'm sorry to say it, the students attracted to popular astronomy courses seem less well equipped to follow mathematical arguments.

For these reasons and others you can well imagine, we must develope and use good demonstrations in astronomy courses.

I have four demonstrations to show you. I don't claim to be the original discoverer of any of them, but so far as I am aware, they are not commonly used by the astronomy teaching community.

My first demonstration is the most complex, dealing with the LUNAR DIURNAL TIDES, a topic which appears in many beginning textbooks. Before showing this demonstration, I'm going to complain about how poorly many current elementary astronomy textbooks handle the subject of ocean tides. Typically, the books vaguely describe the differential forces which arise because various parts of the earth are at different distances from the moon. This is OK as far as it goes, but it doesn't go far enough!

The student has no trouble believing that there should be a bulge in the earth's oceans and atmosphere more or less under the moon. What is harder to understand is the second bulge on the opposite side of the earth. One current textbook says of this second bulge: "Thus the moon pulls earth away from the oceans,which flow into a bulge on the far side." Some discerning students are not convinced by such an explanation and they shouldn't be. It's wrong, or at the most generous, very unclear.

Another book goes into great detail, explaining that the solid earth deforms less than the ocean covering. That's true of course, but it doesn't explain the second bulge either. (If the solid earth didn't deform at all, the tides would be greater. If solid and liquid parts of the earth deformed equally, tides would still be present although probably less evident.) The difficulty in the explanations I mentioned, and many others, from a physics teacher's perspective, is that they ignore the fact that the situation is dynamic, not static. We witness and describe the tides from the earth. But the earth is non-inertial system. This consideration must be included to understand the tides.

Lets's look at the earth-moon motion more carefully, beginning with this very simple representation.

..... Baton device shown and used .....

The motion of the earth and moon system is comparable to this baton-like device. The suspension point = center of mass travels in a near perfect elliptical orbit around the sun while the earth and moon revolve moon-thly around their common center of mass. This motion around the center of mass is very important to the tides. I'll disregard the much slower motion around the sun.

..... Show Transparancy T-1 .....

This transparancy shows the center of mass of the combined earth and moon at point "X" inside the earth, about 1000 miles below the sub lunar point. The upper drawing is a "TOP" view, the plane of the drawing is approximately the equatorial plane but more exactly the plane of the moon's orbit. The lower drawing is a "SIDE" view.

..... Show Transparancy T-2.....

This overlay shows the directions of the moon's gravity field, in black, at three points. This force is always toward the right (positive direction). The centrifugal forces at the same points are shown in red color. Notice that the moon's gravity is strongest at the sublunar point (A), but the centrifugal effect is greatest at the opposite point (C).

I was hesitant to invoke centrifugal forces until I found that Feynman had done the same. Feynman explained the existence of two bulges very clearly and very succinctly in the first volume of his "Lectures". Unfortunately, astronomy textbook writers seem to have overlooked his explanation. The centrifugal force is directed radially outward from the center of mass (the rotation axis). The centrifugal forces adds to the moon's gravitational force at point (A) but subtracts from it at points (E) and (C). Together, these two forces (or force and pseudoforce) account for the existence of two bulges. The next transparancy gives numerical values for the accelerations produced by these two forces at the three points.

..... Show Transparancy T-4.....

The first row of data are calculations of the acceleration produced by the moon's gravity at points A, E and C in meters/sec/sec using the formula given. The second calculation are of the centripetal acceleration at the same points and the third set of numbers are the sums of the first two. Notice that the vector sum is zero at the earth's center, E (Well, nearly zero). Feynman describes the two forces as "balancing" at the earth's center. I am a bit uncomfortable with the word "balance" but "dynamic balance", OK. I want you to especially notice that the vector sums at A and C are toward and away from the moon, respectively, and are about equal in magnitude.

Think of these as small, localized corrections to "g". If you had a free-fall apparatus capable of measuring to 10^{-5} m/sec/sec you could detect these effects directly. These small changes to "g" are a necessary and sufficient condition for forming two bulges

This presentation is about demonstrations for astronomy courses, so I must show you an apparatus which illustrates the two bulges produced when a force substituting for the moon's gravity is countered by centrifugal force. Here's the actual device and here's a drawing of it.

..... Show Transparancy T-5.....

The plane of the drawing matches the "TOP" view in the previous earth-moon drawing. The outer ring (corresponding to the surface of the ocean approximately along the equator) is made of a soft, dense metal (copper). The spring force (substituting for the gravitational pull of the moon) can be adjusted by turning the threaded knob. This support member can flex. In this way the "whole earth" feels the pull of the moon, but near parts distort more than distant parts. The rotation axis in the apparatus is about midway between center and perimeter of the ring. That's inaccurate. To be precise this axis should be located further out from the ring's center.

Under the spring force alone we get an easily perceptable distortion into an egg-shaped oval - not two similar bulges. However when the apparatus is rotated at a suitable rate the second bulge appears. Since the motion is quite rapid, special techniques are needed to display it. A flash picture may be used to "stop" to motion, or a synchonized strobe light. Another technique would be to video tape the motion and show it one frame at a time. Lacking any of these today, I'll simply let the edge of the device swing over the overhead projector and you can see it "bulge" when it is rotated. First we tape a reference scale onto the platform of the projector and carefully note where the "at rest" position of the part of the earth "away from the moon" appears. Now when the rotation begins, you can easily see that this same part is deflected outward. See it? I'm not worried here about getting exactly equal bulges, in fact the other bulge doesn't show with this projector.

.....Operation of model.....

Construction and adjustment of the apparatus is rather tricky. For one thing, you have to be near "dynamic balance" about the eccentric axis or else you will have severe vibration similar to having an "unbalanced" tire on your car. In this apparatus, balance is achieved by building in a large mass on the moonward side of the axis and adjusting its location by a static technique, that is getting the center of mass of the rotating apparatus on the axis of rotation. Auto tires are "static balanced" this same way.

CONCLUSION: We have then, following Feynman's lead, accomplished an adequate explanation of the two tide bulges in simple terms and built a working model on a small scale.

My next demonstration is really a set of charts dealing with the ELLIPTICAL ORBITS OF BINARY STARS. Study of binary star orbits demonstrates the validity of the gravitational force equations beyond the solar system - if this is in doubt. My initial motivation for making this demonstration was to supplement the comments on binary star orbits contained in three very fine 16mm films by ..... Meeks entitled: "Xi Ursae Majoris", "Sirius and the White Dwarf" and "Algol the Demon Star". I suspect that students find it hard to grasp certain of the ideas about orbital motion in these films. The charts are intended to facilitate student understanding of the orbits and especially their tilt in three dimensions.

Here are the kind of orbits that one usually finds for the two stars in a binary system, and a sample of how to use them with your class.

..... Show the Chart with two elliptical orbits ...Cl..

Both stars are in elliptical orbits with the common foci located at the center of mass of the pair. The stars are always at opposite ends of a straight line through this (* point out using meter stick) joining star positions on the two elipses. The line intervals (* here and here) always fit an equation including the mass ratio as on this transparancy.

The two ellipses are "similar" in the same sense that triangles may be similar, with all corresponding lengths (such as long axes) having the ratio: M_A/M_B. The eccentricities of the two ellipses are the same.

Binary stars are often plotted and measured with the brighter star, the primary, (assumed to be the more massive star in these drawings) at the foci of a large ellipse which is thus the the path of the fainter star (the secondary) relative to the brighter. When plotted this way, the single larger ellipse is "similar" to the smaller ellipses in the first chart, but enlarged, and has the same eccentricity.

..... Show second chart with one ellipse..C2...

This chart must be carefully made to match the first one. I will show how to draw matched sets of charts later. In Meeks' films, the narrator comments that the orbits are seldom seen "face on". The true tilt can be calculated but the film is a little too quick here. With these charts, you can illustrate the same more slowly like this....

With reference to the chart C-2 show the following:
1. First, see how this elliptical orbit appears elliptical no matter how the plane is tilted. Circles or straight lines appear with special tilts. I'm assuming that you have a good eye for ellipticity.

2. Note that the long axis line can be seen as the short axis, or as neither long nor short axes. Also, the primary star does not remain on the apparent long axis for most kinds of tilt. Seeing this is more difficult to see. You have to "turn off" your depth perception for a moment.

3. In a astronomical photograph you lack the sense of depth that convinces you at once that the orbit here in this room has been titled. The actual tilt is found by determining the amount the perceived ellipse must be tilted to bring the primary back onto the long axis, and at a particular point on this axis, the foci whose location depends on the eccentricity. The mathematical formulas, of course, involve three dimmensional geometry and are complicated. But with charts such as these you can illustrate the point more thoroughly than Meeks' very brief reference. In the formulas, you tilt the orbits mathematically as I tilted them physically so that the primary would appear on the long axis and at the proper place on this axis.

Now, I wish to describe how you may prepare a set of properly matched ellipses such as I have been using. The exact order of steps may be modified, but I suggest beginning with the largest ellipse then proceeding to the pair of smaller ellipses. Here are the steps described very briefly via transparancies.

..... Show Transparancy T-7.....

1. Select the long axis direction, the primary star location (A) on this axis, and the maximum distance the secondary star (B) is to have on this same axis. Then prepare the usual string needed to draw the ellipse. The double line on this drawing represents the looped string (in red). The primary, as you know, is one of the foci.

2. Select the second foci,F', is placed somewhere between the primary and secondary. Its position fixes the eccentricity of the ellipse. Then draw the full ellipse. The length C is the distance between foci which will appear in a later equation.

Incidentally, the C of M is not yet specified. It moves in an ellipse with a foci at the primary and contained inside the major ellipse on the second chart. I want to emphasize that the choice of mass ratio and the choice of eccentricity of the ellipses are independent choices. With a given mass ratio, you could have circular orbits or any degree of eccentricity you wish.

..... Show Transparancy T-8 .....

We can't stop yet, we've only got one ellipse done.
3. To prepare the pair of smaller ellipses, decide on the mass ratio you wish to represent. Say 2/1 as I have done. Then divide the perimeter of the cord into segments which have the 2/1 ratio by tying it off with a short length of string. (If you simply knot the loop, you lose some perimeter in the knot.) The loop now resembles a figure eight.

4. To draw the pair of ellipses, select the common foci of each ellipse here. This is the center of mass of the pair. Then locate the two "empty foci" according to the formulas here which are functions of the masses and C. After marking the empty foci, the ellipses may be drawn in the usual way using the two short segments of the string, one for each ellipse.

I'd like to point out that a different choice of mass ratio would produce a different pair of ellipses which also "match" the same single ellipse we started with.

..... Show Chart C-3 .....

This third chart shows a pair of ellipses with the mass ratio 3/1 instead of 2/1. This chart was actually prepared before the chart for the 2/1 ratio and with the loop tied off at a different place. Entirely by chance, the 3/1 ratio combined with the original eccentricity gave ellipses which seem to be tangent. At first I thought a mistake had been made. All the drawings I've seen of binary star orbits show two ellipses which intersect. But this chart is perfectly legitimate and matches the first chart. With a very large mass ratio you can even have the situation of the smaller ellipse entirely inside the larger ellipse. Consider, for example the case of the Sun and Jupiter.

In summary of this demonstration, a set of two or more charts can be useful in explaining details of the motion of binary stars, especially the relationship between theoretical motion and actual appearance from our vantage point on earth.

My next "show and tell" is a model of the ECLIPSE SEASON. This is a very simple but useful device to demonstrate the "eclipse seasons", a concept which may escape students when shown through strictly 2-dimensional textbook drawings. The representation is geocentric. The earth is here in the center, the moon on the next orbit and the sun on the outer orbit. These are not to scale of course.

The outer orbit is divided into 12 intervals so that the motion of the sun along the ecliptic can be simulated by moving the sun along one interval per month. Meanwhile, the moon travels much faster, completing one orbit in about one month.

With this model it's easy to show your classes the details involved in producing solar and lunar eclipses. An eclipse requires very close allignment of the geometric centers of sun and moon as seen from the earth. This occurs rarely because the planes of the two orbits are tilted by 5° while the images of sun and moon are each about ½° wide. To produce an eclipse both sun and moon must be quite near to the intersection of the orbital planes, the "line of nodes". Thus there is a short "window" in time called the "eclipse season".

The apparatus also permits motion of the line of nodes by sliding the outer tubing through the metal support. All of this allows for a three dimensional model that accounts for the following facts:

1. Solar eclipses are usually spaced at about six month intervals. The same is true of lunar eclipses. This six month interval occurs because both sun and moon must be near the line of nodes and it takes the sun almost six months to move from one end of the line of nodes to the opposite end.

2. A solar and lunar eclipse often occur about 14-15 days apart. Because the moon's angular size is slightly larger than the sun's at perigee, the "window" near the line of nodes is a bit over 29 days long, enough to accomodate the two eclipses described.

3. In some years there are three solar eclipses, if the first occurs early in January. A second eclipse will then occur in June or July. Due to slow retrograde motion of the line of nodes a third eclipse can occur in late December. The motion of the line of nodes has a cause akin to the precession of the equinoxes and a period of 18.6 years.

4. On very rare occasions, there can be up to five (NO KIDDING!) solar eclipses in a single year. The most recent time this occured was in 1935. The first two would be in January, about 30 days apart. The next pair in June/July, and the fifth in late December. The motion of the line of nodes and the maximum width of the "window" near the line of nodes are both critical here, and of course starting early in January.

My last demonstration concerns ABSORPTION SPECTRA. The most common kind of spectra from astronomical sources is absorption spectra in which the blackbody spectra from a star's deep photosphere is diminished at certain wavelengths by re-absorption in slightly cooler upper layers. The spectrum of the sun contains some 30,000 narrow absorption lines superimposed on the continuous blackbody spectrum. Other stars show similar spectra as do distant galaxies, quasars, etc.

Unfortunately, the usual absorption spectra demonstrations are not conveniently demonstrable to large audiences. The technique which uses a sodium flame is suitable for individual observation or small classes. Besides, sodium has only two strong absorption lines very close together in the visible range. I'm not personally familiar with the Iodine technique.

I will show you the absorption spectra of a solution of Erbium Chloride, which makes a much better demonstration, I believe. To see the spectra, hold the small pieces of diffraction grating up close to your eye with the long dimension horizontal while you look at the light source up here in front.

POINT OUT THESE FEATURES:

1. First the Continuous spectrum alone from the filament lamp.

2. See the absorption lines when the solution is along your line of sight.

3. Notice that there are several rather narrow lines visible.

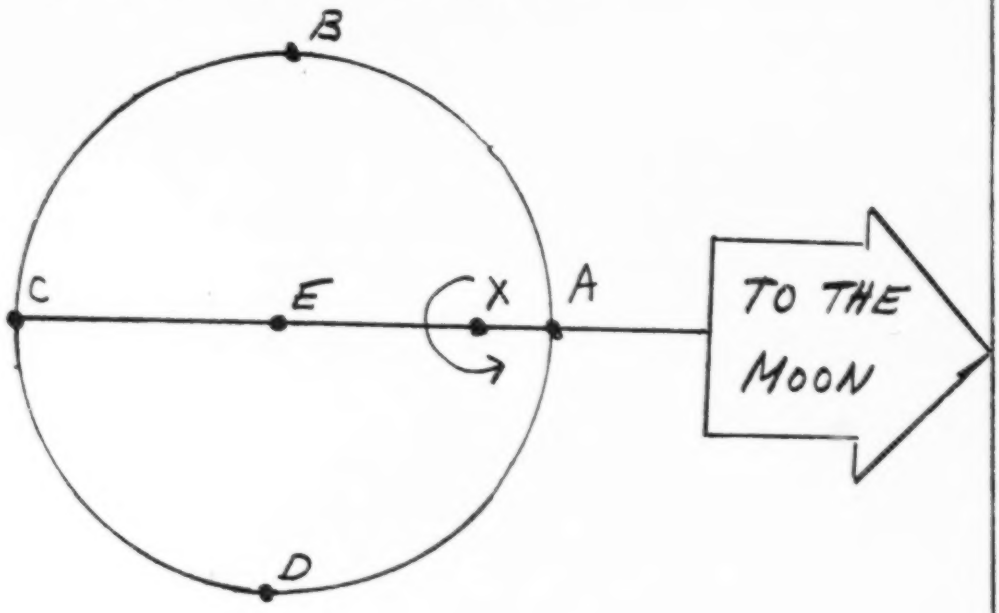
Almost all rare earth compounds have sharp absorption lines but erbium is one of the cheaper ones and it has many lines spread over the whole visible spectrum. The chloride is easily soluable in water. Your chemistry departments can find you catalogues for ordering Erbium Chloride. Small absorption cells require less than 25 grams, at a cost around $25. I ordered 100 grams recently at a cost of $68.

CONCLUSION: Absorption cells containing solutions of rare earth compounds are better for use with large classes common in beginning astronomy classes than sodium flames.

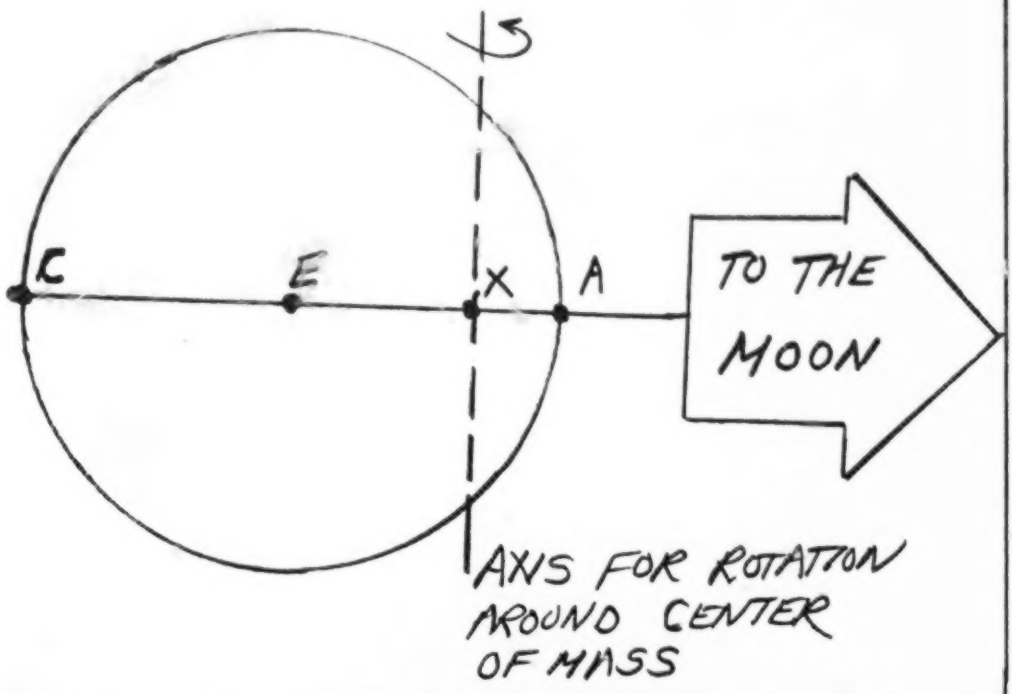
This concludes my demonstrations. You are welcome to examine them up front as time permits. If you have use for the diffraction grating, keep it, but otherwise return them to me up front. If you have questions, please speak loudly, my hearing is not good.

Any questions?

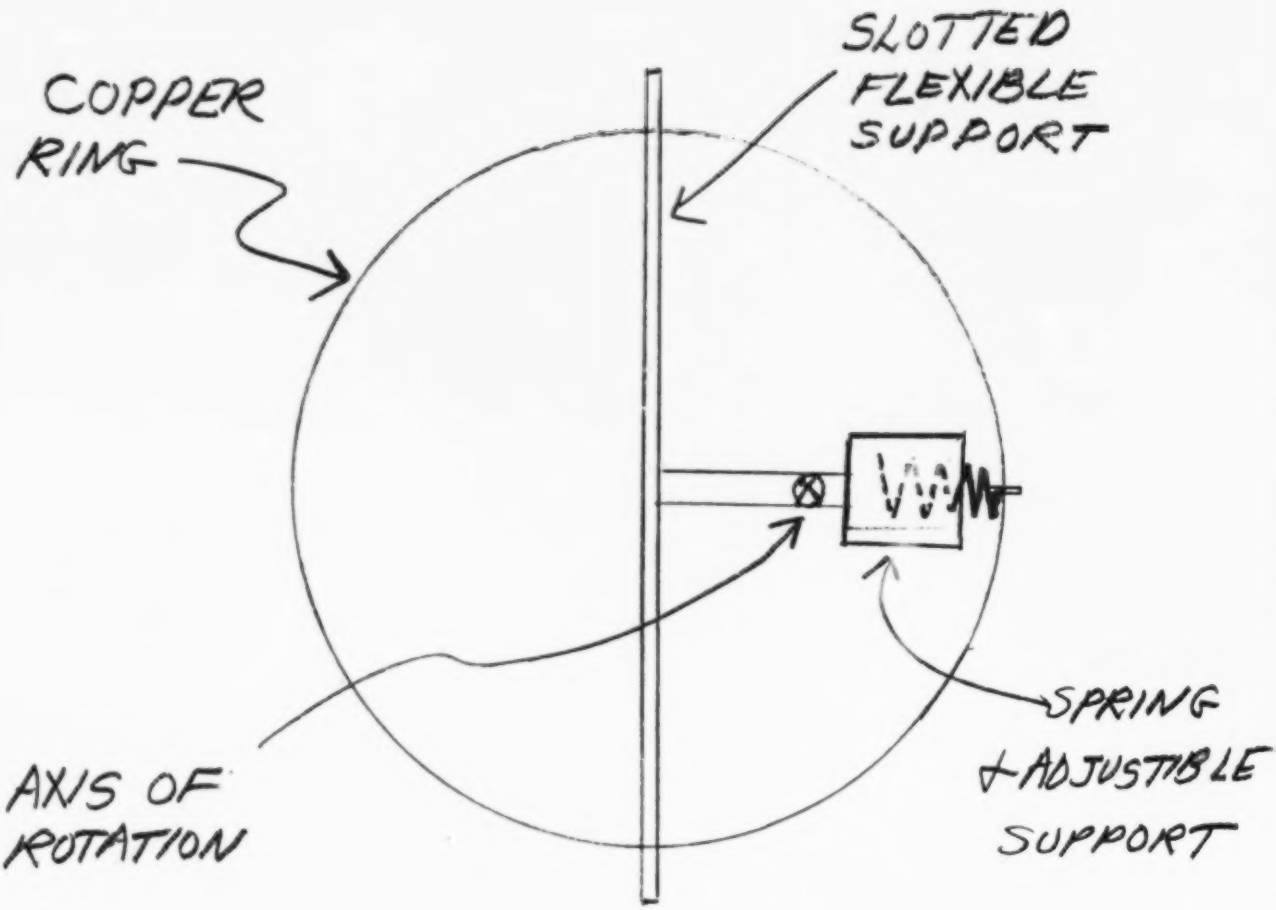
"TOP" VIEW OF EARTH

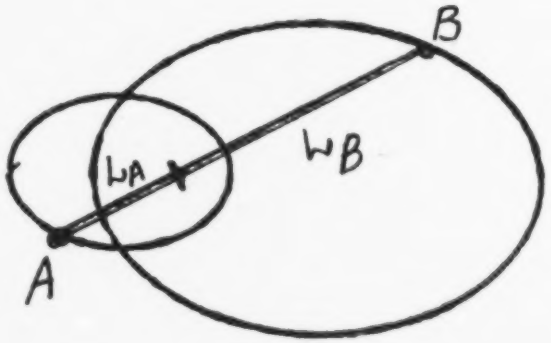


"SIDE" VIEW OF EARTH



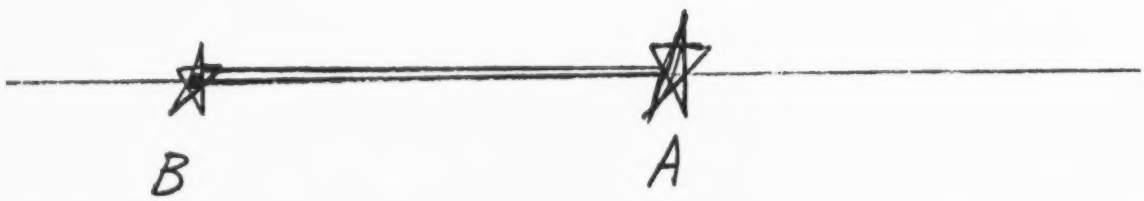
ANTI-LUNAR POINT (C)	CENTER OF EARTH (E)	SUB-LUNAR POINT (A)
ACCELERATION DUE TO MOON'S GRAVITY (M/SEC^2) $a = GM/d^2$		
$+3.212 \times 10^{-5}$	$+3.319 \times 10^{-5}$	$+3.429 \times 10^{-5}$
CENTRIFUGAL ACCELERATION (M/SEC^2) $a = \omega^2 d$		
-7.832×10^{-5}	-3.314×10^{-5}	$+1.209 \times 10^{-5}$
-4.620×10^{-5}	$.005 \times 10^{-5}$	4.628×10^{-5}


COPPER RING
SLOTTED FLEXIBLE SUPPORT
AXIS OF ROTATION
SPRING + ADJUSTIBLE SUPPORT

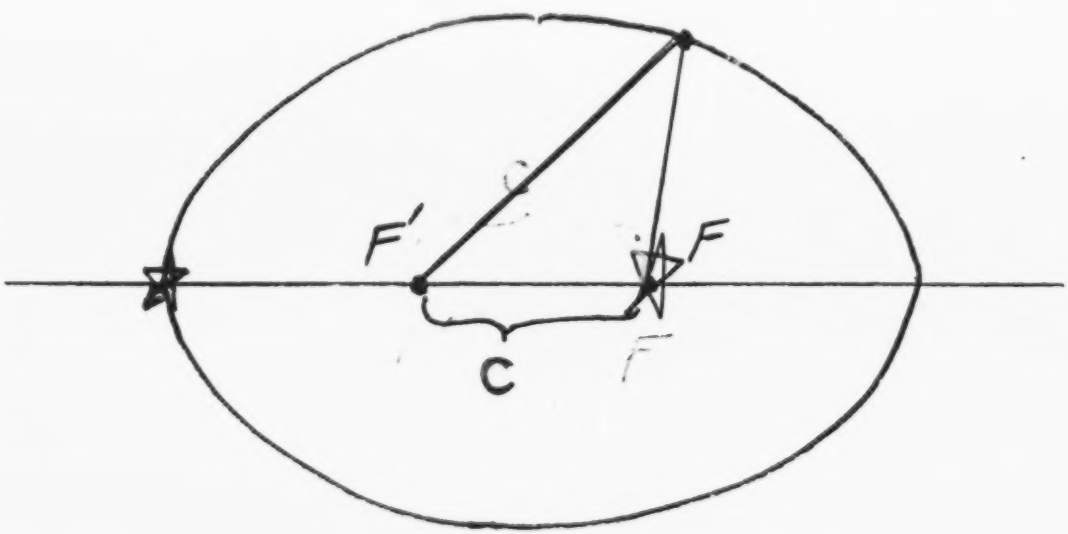


$$\frac{L_A}{L_B} = \frac{M_B}{M_A} = \frac{1}{2}$$

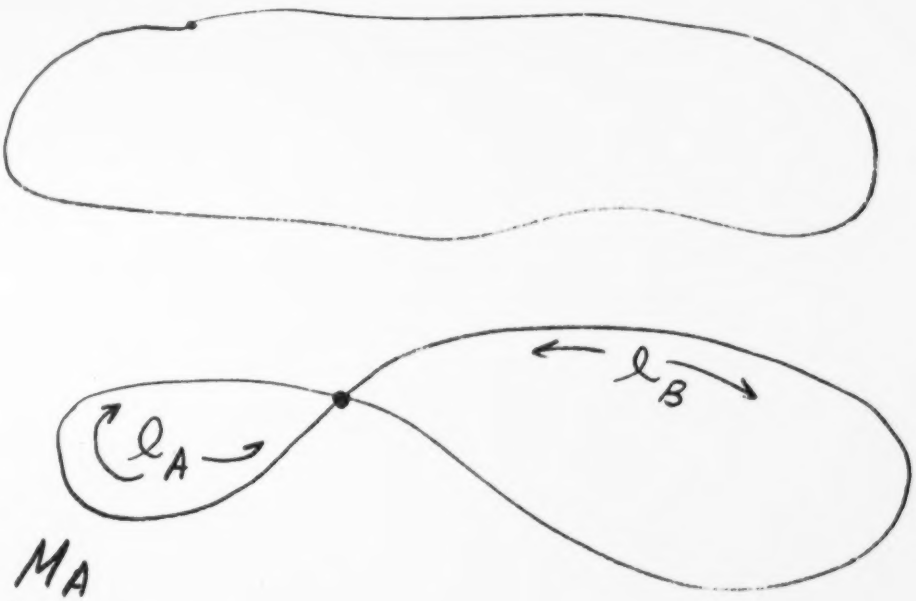
1.



2.

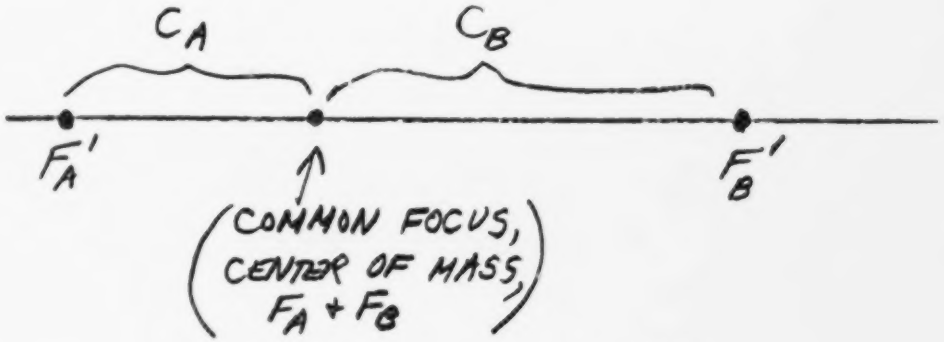


3.



$$\frac{\ell_B}{\ell_A} = \frac{M_A}{M_B}$$

4.



$$C_A = \frac{CM_B}{M_A+M_B} \quad , \quad C_B = \frac{CM_A}{M_A+M_B}$$